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Scenario optimization modeling approach for design and management of biomass-to-biorefinery supply chain system

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HIGHLIGHTS

- A scenario optimization model addressing weather uncertainty in BSC is proposed.
- The modeling objective is to minimize the cost of biomass supply to biorefinery.
- Field harvest work hours influence major cost-related decisions in the BSC system.
- Yield of biomass is a crucial factor in determining the feasibility of BSC system.
- Biomass storage method selected is dependent on the cost and dry matter loss during storage.

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ABSTRACT

The aim of this study was to develop a scenario optimization model to address weather uncertainty in the Biomass Supply Chain (BSC). The modeling objective was to minimize the cost of biomass supply to biorefineries over a one-year planning period using monthly time intervals under different weather scenarios. The model is capable of making strategic, tactical and operational decisions related to BSC system. The performance of the model was demonstrated through a case study developed for Abengoa biorefinery in Kansas. Sensitivity analysis was done to demonstrate the effect of input uncertainty in yield, land rent and storage dry matter loss on the model outputs. The model results show that available harvest work hours influence major cost-related decisions in the BSC.

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1. Introduction

Presently, biofuels account for around 3% of the transport fuel of the world and is estimated to increase by 30% or more by 2050 (BP, 2013). It has also been estimated that 30% of the petroleum-based energy consumption in the U.S. can be replaced with biomass, which will require roughly 1 billion tons of biomass (Perlack et al., 2005). But, producing and supplying large quantities of low density biomass to the biorefineries is challenging. Feasibility of alternative energy sources such as biodiesel and hydrogen is also investigated but still remains largely in research phase. Major barriers preventing commercialization of cellulosic biorefineries is its production technology, limited biomass availability, and complex Biomass Supply Chain (BSC) system (Sharma et al., 2013). It is estimated that biomass supply accounts for 20–30% of the ethanol production cost, of which 90% is associated with logistical processes (Eksioglu et al., 2009).

Recently, there has been extensive focus by researchers on developing mathematical models for BSC design and management. Majority of the research works have developed mixed-integer linear programming models with decision making capability ranging from strategic to operational-level (Sharma et al., 2013). Commonly used quantitative performance measure for BSC models are cost minimization or profit maximization (Gunnarsson et al., 2004; Huang et al., 2010; Tembo et al., 2003; Zamboni et al., 2009). New approaches for modeling BSC are also introduced such as state-task-network (Dunnett et al., 2007), spatially explicit (Zamboni et al., 2009), multi-stage (Huang et al., 2009), multi-echelon (Dal-Mas et al., 2011; Giarola et al., 2012), time-staged multi-commodity (An et al., 2011), multi-objective/multi-period (You et al., 2011; You and Wang, 2011), two-stage linear programming (Cundiff et al., 1997), techno-economic system model (Svanberg et al., 2013) and two-stage stochastic programming (Chen and Fan, 2012) models. These approaches have increased BSC decision

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making capabilities, and also address some of the critical issues and complexity associated with the BSC system. Studies by You and Wang (2011) and You et al. (2011) provide comprehensive assessment of the BSC with a focus on economic, environmental, and social impact of biofuel production. Majority of the models developed for BSC emphasize on considering sources of variability due to process and environment into the models for better management (An et al., 2011; Huang et al., 2010; You and Wang, 2011). Some of the models developed for BSC consider uncertainty in demand and price by formulating different scenarios (Akgul et al., 2010; Dal-Mas et al., 2011; Zamboni et al., 2009). The impact of weather uncertainty on BSC is crucial as it limits the amount of biomass supplied to a biorefinery and this variability is not considered by majority of the models.

Cundiff et al. (1997) developed a two-stage linear programming model for herbaceous biomass supply from 20 different farm locations to a centrally located biorefinery. The model determines monthly material flow and storage capacity expansion for each producer for four weather scenarios. However, the model does not capture complex BSC structure, and does not estimate number of equipment units required and storage treatments used. Therefore, to explicitly account for weather uncertainty and provide enhanced decision making capabilities for BSC, a scenario optimization model was developed in this present study. The component of weather uncertainty was incorporated into the model by estimating work hours available for harvesting biomass. The model provides decision about acres leased, material flow, number of harvesting units, in-field transportation units and transportation units purchased and rented, allocation of machinery units, and storage treatments used. The model also considers the technical and operational characteristics of the machinery units, and before-frost and after-frost harvesting of biomass. The specific objectives of the study were:

- To formulate a scenario optimization model for biomass supply to a biorefinery under weather uncertainty.
- To develop a case study for switchgrass supply chain to the Abengoa Biorefinery (AB) at Hugoton, Kansas.

2. Methodology

2.1. Mathematical model

A scenario optimization model was developed to minimize cost of biomass supply to a biorefinery considering harvest, transportation, and storage costs. One year planning period with monthly time increments was considered. The model utilizes the yearly weather data to make the harvesting work-hour decision and each year was considered as a weather scenario. The daily weather data was obtained from the Oklahoma Mesonet for determining the work-hours available for harvesting (Mesonet, 2012). Each weather scenario was assigned equal probability of occurrence as the weather pattern was considered to be random and unpredictable. The soil moisture content, rain, snow, and daylight hours determine the number of harvest work-hours available in a time period. The network structure consists of biomass source sites, storage sites, and a biorefinery site. The harvest unit consists of a self-propelled windrower, a rake with a tractor and a large square baler with a tractor. The in-field transportation unit comprised of a bale

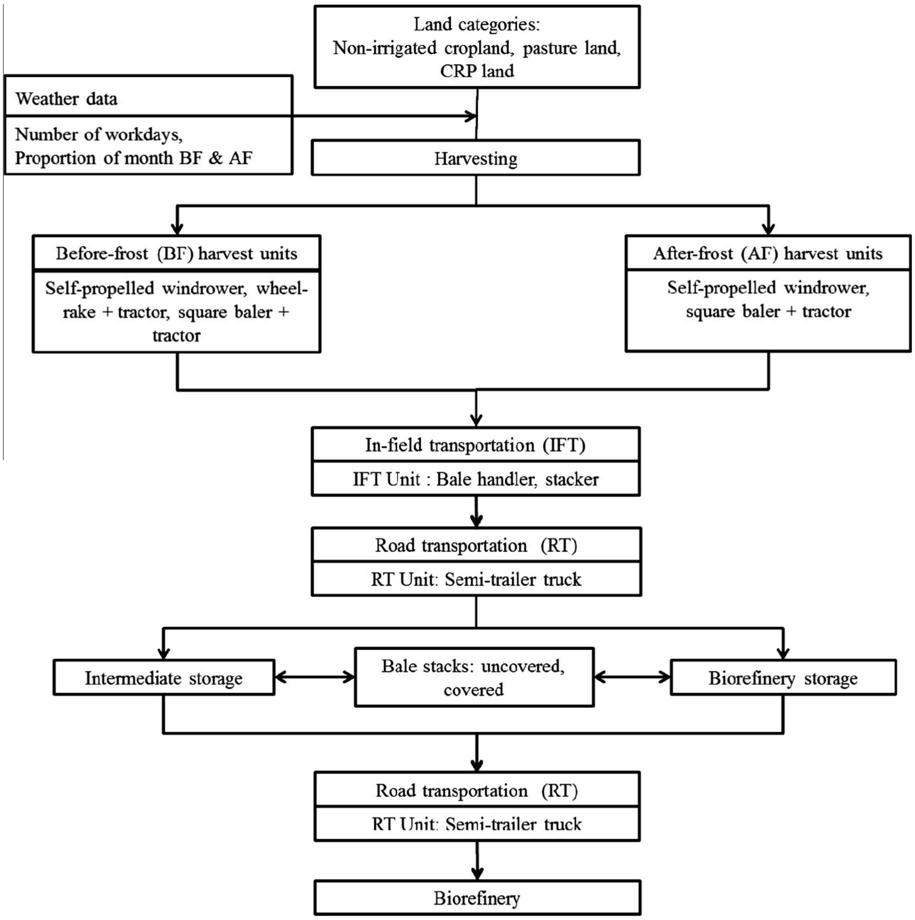
Land categories:
Non-irrigated cropland, pasture land, CRP land
Weather data
Number of workdays, Proportion of month BF & AF
Harvesting
Before-frost (BF) harvest units
Self-propelled windrower, wheel-rake + tractor, square baler + tractor
After-frost (AF) harvest units
Self-propelled windrower, square baler + tractor
In-field transportation (IFT)
IFT Unit : Bale handler, stacker
Road transportation (RT)
RT Unit: Semi-trailer truck
Intermediate storage
Bale stacks: uncovered, covered
Biorefinery storage
Road transportation (RT)
RT Unit: Semi-trailer truck
Biorefinery

Fig. 1. Schematic of various components considered in the model.

handler and a bale stacker. The road transportation unit consists of a semi-truck with trailer. Fig. 1 presents the schematic of different components considered in the model. Notations for indices, parameters, and decisions variables used for the model formulations are summarized in Tables 1 and 2.

2.1.1. Objective function

The cost minimization objective function for the BSC system is represented by Eq. (1). The cost components for this economic objective function were biomass procuring, transportation, storage, rented and purchased equipment cost presented in Eqs. (2)–(13). The value of excess biomass sold to outside sources in a weather scenario (where more than the required biomass is produced) was subtracted from the total cost. Constraints for the model are presented in Eqs. (14)–(34).

$$\begin{aligned} Minimize\_Cost = {} & C_{bp} + C_{al} + C_{fchu} + C_{vchu} + C_{fciftu} + C_{vciftu} \\ & + C_{fctu} + C_{vctu} + C_{vcru} + C_{cbos} + C_{cstor} - P_{sfl} \end{aligned} \tag{1}$$

Biomass procuring cost (C_{bp})

$$\begin{aligned} C_{bp} = {} & \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} tbf_{litw} \times CPROC \times BF_{tw} \times PWS_{w} \right) \\ & + \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} taf_{litw} \times CPROC \times (1 - BF_{tw}) \times PWS_{w} \right) \end{aligned} \tag{2}$$

Cost of acres leased (C_{al})

$$C_{al} = \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{w=1}^{W} acrelease_{li} \times CACRE_{li} \times PWS_{w} \right) \tag{3}$$

Fixed cost (C_{fchu}) and variable cost (C_{vchu}) of harvest units

$$C_{fchu} = (hubf \times FCHUBF) + (ahuaf \times FCHUAF) \tag{4}$$

$$\begin{aligned} C_{vchu} = {} & \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} sabf_{litw} \times VCHUBF \times BF_{tw} \times PWS_{w} \right) \\ & + \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} saaf_{litw} \times VCHUAF \times (1 - BF_{tw}) \times PWS_{w} \right) \end{aligned} \tag{5}$$

Fixed cost (C_{fciftu}) and variable cost (C_{vciftu}) of in-field transportation units

$$C_{fciftu} = ntul \times FCTUL \tag{6}$$

$$\begin{aligned} C_{vciftu} = {} & \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} tbf_{litw} \times VCTUL \times BF_{tw} \times PWS_{w} \right) \\ & + \left(\sum_{l=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} taf_{litw} \times VCTUL \times (1 - BF_{tw}) \times PWS_{w} \right) \end{aligned} \tag{7}$$

Fixed cost (C_{fctu}) and variable cost (C_{vctu}) of road transportation units

$$C_{fctu} = ntu \times FCTU \tag{8}$$

$$\begin{aligned} C_{vctu} = {} & \left(\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{w=1}^{W} tssi_{ijtw} \times VCTUSI_{ij} \times PWS_{w} \right) \\ & + \left(\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} tssb_{itw} \times VCTUSB_{i} \times PWS_{w} \right) \\ & + \left(\sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{w=1}^{W} tsib_{jtw} \times VCTUIB_{j} \times PWS_{w} \right) \end{aligned} \tag{9}$$

Variable cost (C_{vcru}) of rented harvest and in-field transportation units

$$\begin{aligned} C_{vcru} = {} & \left(\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} rnhubf_{itw} \times CRHUBF \times BF_{tw} \times WDAY_{tw} \right) \\ & + \left(\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} rnhuaf_{itw} \times CRHUAF \times (1 - BF_{tw}) \times WDAY_{tw} \right) \\ & + \left(\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} renptul_{itw} \times CRNPTUL \times WDAY_{tw} \right) \end{aligned} \tag{10}$$

Cost of purchasing biomass from outside source (C_{cbos})

$$C_{cbos} = \sum_{t=1}^{T} \sum_{w=1}^{W} outdem_{tw} \times COUTDEM \times PWS_{w} \tag{11}$$

Cost of storing biomass with a specific storage method (C_{cstor})

Table 1
Model indices and input parameters notations and description.

Index	Description
I	Set of biomass source sites indexed by i
J	Set of inventory sites indexed by j
l	Set of land categories indexed by l
S	Set of storage method indexed by s
T	Set of time periods indexed by t
W	Set of weather scenarios indexed by w
Parameters	Description
$ACRELAND_{li}$	Acres of land under land category l in source site i (acres)
BF_{tw}	Before-frost time period t in weather scenario w (0 or 1)
$CACRE_{li}$	Cost of leasing acres for biomass production under land category l in source county i ($/acre)
CAPHUAF	Capacity of harvest unit after-frost (acres/hr.)
CAPHUBF	Capacity of harvest unit before-frost (acres/hr.)
CAPSTOR	Capacity of storage unit (tons)
CAPTU	Capacity of road transportation unit (tons/load)
CAPTUL	Capacity of in-field transportation unit (tons/hr.)
COUTDEM	Cost of biomass supply from outside source ($/ton)
CPROC	Cost of procuring biomass ($/ton)
CRHUBF	Rental rate for the harvest unit before-frost ($/day)
CRHUAF	Rental rate for the harvest unit after-frost ($/day)
CRNPTUL	Rental rate for the in-field transportation units ($/day)
DEN_{t}	Demand of biomass in a time period t (tons)
$DMLOSS_{s}$	Dry matter loss for storage method s (fraction)
FCHUAF	Annual fixed cost of harvest unit after-frost ($/year)
FCHUBF	Annual fixed cost of harvest unit before-frost ($/year)
$FCSTOR_{s}$	Fixed cost of storing biomass with storage method s ($/unit)
FCTU	Annual fixed cost of transportation unit ($/year)
FCTUL	Annual fixed cost of in-field transportation unit ($/year)
htrip	Road round trip hours (1/hr.)
$INVEND_{j}$	Ending inventory at inventory site j (tons)
$INVSTART_{j}$	Beginning inventory at inventory site j (tons)
LEN_{tw}	Length of time period t in weather scenario w (hr./tp)
PFL	Value of biomass sold to outside source/feedlot ($/ton)
$PROP_{li}$	Proportion of land category l at source site i suitable for biomass cultivation (fraction)
PWS_{w}	Probability of weather scenario w (fraction)
VCHUAF	Variable cost of harvest unit after-frost ($/acre)
VCHUBF	Variable cost of harvest unit before-frost ($/acre)
$VCTUIB_{j}$	Variable cost of transporting biomass from inventory site j to biorefinery site ($/ton)
VCTUL	Variable cost of in-field transportation unit ($/ton)
$VCTUSB_{i}$	Variable cost of transporting biomass from source site i to biorefinery site ($/ton)
$VCTUSI_{ij}$	Variable cost of transporting biomass from source site i to inventory site j ($/ton)
WDH_{tw}	Number of harvesting workdays available in a time period t and weather scenario w
$YADJ_{t}$	Yield adjustment factor for time period t (fraction)
$YIELD_{l}$	Yield of biomass for land category l (tons/acre)

$$C_{cstor} = \sum_{s=1}^{S} nstor_s \times FCSTOR_s \tag{12}$$

Value of biomass sold to feedlot (P_{sfl})

$$P_{sfl} = \left(\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{w=1}^{W} tsfl_{litw} \times PFL \times PWS_w\right) \tag{13}$$

2.1.2. Constraints

2.1.2.1. Supply constraints. Eqs. (14) and (15) presents constraints that ensure that the total acres harvested must not exceed the total acres leased for biomass production. The acres leased were equivalent to proportion of the total available acres in the biomass source site. The proportion of a land type available for biomass production in a biomass source site was estimated based on previous literature and can be varied depending on geographical area and land type.

$$\sum_{t=1}^{T}(sabf_{litw} \times BF_{tw} + saaf_{litw} \times (1 - BF_{tw})) \\ = acrelease_{li} \times PROP_{li} \quad \forall l, i, w \tag{14}$$

$$acrelease_{li} \leqslant ACRELAND_{li} \times PROP_{li} \quad \forall l, i \tag{15}$$

Eqs. (16) and (17) ensure that the total tonnage procured by the biorefinery equals the acres of biomass harvested multiplied by the yield and yield adjustment factor. The yield adjustment factor varies between 0 and 1, and adjusts the change in yield of biomass with progressing harvest season.

$$tbf_{litw} = sabf_{litw} \times YADJ_t \times YIELD_l \times BF_{tw} \quad \forall l, i, t, w \tag{16}$$

$$taf_{litw} = saaf_{litw} \times YADJ_t \times YIELD_l \times (1 - BF_{tw}) \quad \forall l, i, t, w \tag{17}$$

2.1.2.2. Balance constraints. The balance constraints are imposed on the biomass source site, biorefinery site, and inventory site. It was assumed that biomass was not stored at the biomass harvesting site. Therefore, the amount of biomass harvested at the biomass source site was equal to the total amount of biomass transported to the inventory site and the biorefinery site and the excess biomass if any sold to the feedlot (Eq. (18)).

$$\sum_{l=1}^{L}(tbf_{litw} \times BF_{tw} + taf_{litw} \times (1 - BF_{tw})) \\ = tssb_{itw} + \sum_{j=1}^{J} tssi_{ijtw} + \sum_{l=1}^{L} tsfl_{litw} \quad \forall i, t, w \tag{18}$$

At the biorefinery site, the balance constraint represents that biomass transported to the biorefinery site from the source site and inventory site plus the unmet demand of biomass must be equal to the demand of biorefinery (Eq. (19)). If there is unmet demand, biomass will be purchased from the outside sources.

$$\sum_{j=1}^{J} tsib_{jtw} + \sum_{i=1}^{I} tssb_{itw} + outdem_{tw} = DEN_t \quad \forall t, w \tag{19}$$

At the inventory site, the total biomass stored at inventory site in a time period is equal biomass transported from the source site to the inventory site in a time period plus biomass stored at the inventory site at the end of previous time period less any storage losses (Eq. (22)). The constraints (Eqs. (20) and (21)) allocate biomass transported to the inventory site from biomass source sites into different storage methods. Eq. (23) shows that the safety stock of biomass should be maintained at the inventory site at the end of planning horizon. The amount of biomass stored at inventory site was constrained by the storage unit capacity and number of storage units endogenously determined by the model (Eq. (24)).

$$\sum_{i=1}^{I} tssi_{ijtw} = \sum_{s=1}^{S} tasi_{jstw} \quad \forall j, t, w \tag{20}$$

$$tsib_{jtw} = \sum_{s=1}^{S} ttis_{jstw} \quad \forall j, t, w \tag{21}$$

$$sti_{jstw} = INVSTART_j + tasi_{jstw} - ttis_{jstw} + (if(t > 1) \\ (sti_{js(t-1)w} \times (1 - DMLOSS_s, 0))) \quad \forall j, s, t, w \tag{22}$$

$$sti_{j,s=1,t=12,w} >= INVEND_j + \sum_{t=1}^{T} outinv_{tw} \quad \forall j, w \tag{23}$$

$$\sum_{j=1}^{J} sti_{jstw} <= nstor_s \times CAPSTOR \quad \forall s, t, w \tag{24}$$

2.1.2.3. Harvest units constraints. The total number of harvest units after-frost is equal to the number of harvest units used during the period before-frost along with additional units required to handle the heavier demands of added acreage for after-frost harvesting (Eq. (25)).

$$huaf = hubf + ahuaf \tag{25}$$

Eq. (26) represent constraints that ensures the biomass acres harvested may not exceed the combined capacity of harvest units allocated to the biomass source site. The work hours available for harvesting biomass in a weather scenario and harvesting unit capacity, constraints the amount of biomass harvested at the biomass source site. Similarly, work hours available in a weather scenario and harvesting unit capacity constraints the amount of biomass transported during in-field transportation (Eq. (27)). Eqs. (28)–(33) represent constraints that ensure that the sum of the units (harvest and in-field transportation) used for biomass harvesting and handling at the biomass source sites may not exceed the total number of units determined by the model.

$$(sabf_{litw} \times BF_{tw} + saaf_{litw} \times (1 - BF_{tw})) < \\ = (nhubf_{itw} \times CAPHUBF \times BF_{tw} + nhuaf_{itw} \times CAPHUAF \times (1 \\ - BF_{tw})) \times WDH_{tw} \quad \forall i, t, w \tag{26}$$

$$tbf_{litw} \times BF_{tw} + taf_{litw} \times (1 - BF_{tw}) \\ \leqslant nptul_{itw} \times CAPTUL \times WDH_{tw} \quad \forall l, i, t, w \tag{27}$$

$$nhubf_{itw} = nphubf_{itw} + rnhubf_{itw} \quad \forall i, t, w \tag{28}$$

$$nhuaf_{itw} = nphuaf_{itw} + rnhuaf_{itw} \quad \forall i, t, w \tag{29}$$

$$nptul_{itw} = npurtul_{itw} + renptul_{itw} \quad \forall i, t, w \tag{30}$$

$$\sum_{i=1}^{I} nphubf_{itw} = hubf \times BF_{tw} \quad \forall t, w \tag{31}$$

$$\sum_{i=1}^{I} nphuaf_{itw} = ahuaf \times (1 - BF_{tw}) \quad \forall t, w \tag{32}$$

$$\sum_{i=1}^{I} npurtul_{itw} = ntul \quad \forall t, w \tag{33}$$

Table 2
Model decision variables notations and description.

Variables	Description
$acrelease_{li}$	Total acres leased for biomass production under land category l in source site s
$ahuaf$	Number of additional harvest units purchased after-frost
$huaf$	Total number of harvest units after-frost
$hubf$	Number of harvest units purchased before-frost
$nhuaf_{itw}$	Total harvest units after-frost allocated to source site i in time period t and weather scenario w
$nhubf_{itw}$	Total harvest units before-frost allocated to source site i in a time period t and weather scenario w
$nphuaf_{itw}$	Purchased harvest units after-frost allocated to source site i in a time period t and weather scenario w
$nphubf_{itw}$	Purchased harvest units before-frost allocated to source site i in a time period t and weather scenario w
$nptul_{itw}$	Total in-field transportation units allocated to source site i in a time period t and weather scenario w
$npurtul_{itw}$	Purchased in-field transportation units allocated to source site i in a time period t and weather scenario w
$nstor_{s}$	Number of storage units of storage method types
ntu	Number of transport units purchased
$ntul$	Number of in-field transportation units purchased
$outdem_{tw}$	Demand met from outside supply in time period t and weather scenario w
$outinv_{tw}$	Inventory safety stock met from outside supply in time period t and weather scenario w
$renptul_{itw}$	Rented in-field transportation units allocated to source site i in a time period t and weather scenario w
$rnhuaf_{itw}$	Rented harvest units after-frost allocated to source site i in a time period t and weather scenario w
$rnhubf_{itw}$	Rented harvest units before-frost allocated to source site i in a time period t and weather scenario w
$saaf_{litw}$	Acres of biomass harvested from land category l in source site i after-frost in time period t under weather scenario w
$sabf_{litw}$	Acres of biomass harvested from land category l in source site i before-frost in time period t and weather scenario w
sti_{jstw}	Tons of biomass stored at inventory site j under storage method s in time period t and weather scenario w
taf_{litw}	Tons of biomass from source county i and land category l after-frost in time period t under weather scenario w
$tasi_{jstw}$	Tons of biomass transported from source site i to inventory site j allocated to storage method s in time period t and weather scenario w
tbf_{litw}	Tons of biomass from source county i and land category l before-frost in time period t under weather scenario w
$tsfl_{litw}$	Tons of biomass biomass harvested from land category l in source site i sold to feedlot in a time period t and weather scenario w
$tsib_{jtw}$	Tons of biomass transported from inventory site j to biorefinery site in time period t and weather scenario w
$tssb_{itw}$	Tons of biomass transported from source site i to biorefinery site in time period t and weather scenario w
$tssi_{ijtw}$	Tons of biomass transported from source site i to inventory site j in time period t and weather scenario w
$ttis_{jstw}$	Tons of biomass transported from inventory site j to biorefinery site allocated to storage method s in time period t and weather scenario w

2.1.2.4. Road transportation units constraints. This constraint ensures that the biomass tonnage transported from the biomass source site to inventory site, inventory site to biorefinery site and source site to biorefinery site may not exceed the total number of transportation units (Eq. (34)). The transportation unit capacity is constrained by the length of time period and number of trips made by transportation unit in a time period.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} tssi_{ijtw} + \sum_{i=1}^{I} tssb_{itw} + \sum_{j=1}^{J} tsib_{jtw} \leqslant CAPTU \times LEN_{tw} \times htrip \quad \forall t, w \tag{34}$$

2.2. Case study description

The case study was developed for the Abengoa Biorefinery (AB) at Hugoton, Kansas (KS). AB considers switchgrass to be a potential future biofeedstock and therefore, it is considered as the biomass used by biorefinery for this case study analysis. In addition, switchgrass has a wide harvest window of eight months starting from July to February, which results in only four months of non-harvesting season. Twelve weather scenarios from 1998–2010 with equal probability of occurrence of 0.0831(1÷12) were considered. The 50 mile radius was defined as the feedstock procurement area which includes Morton, Stanton, Grant, Haskell, Seward, and Stevens counties in KS and Texas County in Oklahoma (OK) (DOE/EIS, 2010). For the operation of the biorefinery a daily demand of 800 dry tons of switchgrass was considered with a nominal production schedule of 350 days per year (DOE/EIS, 2010). Since switchgrass is not commercially available in the feedstock procurement area, an assumption was made that the farmers would convert their land to switchgrass production. It was assumed that non-irrigated harvested cropland, permanent pasture, and expiring and not re-enrolled CRP acres 2011 and 2012 will be used for switchgrass production. The proportion of cropland and pastureland used for switchgrass production in the source sites was adapted from the Billion-Ton Update report (Perlack and Stokes, 2011) and was 25% and 50% for non-irrigated cropland and pastureland, respectively. It was also assumed that up to 50% of CRP land can be used for switchgrass production (Khanna et al., 2011). Yield of switchgrass decrease with maturity and the model assumes a yield loss factor of 5% per month from September through February (Epplin et al., 2007). The AB anticipates an average yield of 1.5–3.0 dry tons per acre for switchgrass from the soil types and climatic patterns present in the region (DOE/EIS, 2010). The yield of switchgrass was assumed to be two dry tons per acre for the base scenario. The farmers supplying biomass to AB were given three payment options (a fixed price option, a lower base price with revenue sharing and a lower base price with compensation for nutrient replacement) for biomass cost per ton. The fixed price option of $15 per dry ton was used for this study (Bevill, 2011). The cost of biomass purchased from outside source was assumed to be $90 per dry ton, which was 50% higher than the $60 per dry ton delivered cost of biomass (Perlack and Stokes, 2011) and cost of selling excess biomass produced in a weather scenario to feedlot was assumed to be 25% of dollar per ton cost of biomass. Five inventory sites were selected based on road accessibility and the distance from the biorefinery site of about 30 miles. ArcGIS 10 software (ESRI. ArcGIS 10.1) was used for selection of the inventory sites. One year safety stock (level of extra stock of biomass maintained at inventory sites to minimize the risk of stakeouts or not having biomass available to meet the biorefinery demand) of biomass at the inventory sites was maintained. The ending inventory was assumed to be equal to beginning inventory. The distances between the sites was calculated using the great circle distance formula.

Two storage methods were considered: unprotected bales on the ground and tarped bales on gravel with dry matter loss of 0.33% for each method. The dry matter loss values for each storage method were obtained from experiments conducted in the Oklahoma Panhandle for storing square switchgrass bales (E. Miller, 2012, Dry matter loss for square bales stored in

Panhandle, Oklahoma. Personal communication, Oklahoma State University). The reason for same dry matter loss values was attributed to extremely dry weather conditions during the storage period (2010-2011). The size of a storage bale stack was limited to 100 tons and each stack was considered to be separated by at least 20 ft., as required by the International Fire Code (ICC, 2003). Switchgrass can be harvested before-frost and after-frost. The first freeze in Oklahoma usually occurs in late October or early November (Koss et al., 1998; Sharma et al., 2011). A Matlab program (MathWorks®. Ver., R2009b.) was developed to determine the time periods before-frost and after-frost. A day was considered to be before-frost if the minimum temperature was above 32°F. If 60% of the days in a month met the criteria, the month was considered to be "before-frost" for classification purposes.

2.3. Machine performance

2.3.1. Harvest unit (windrower, rake and baler)

Biomass such as switchgrass can be mowed using standard hay equipment (Christensen and Koppenjan, 2010). A 16-ft. self-propelled windrower was assumed to be used for harvesting switchgrass. The working throughput capacity of a self-propelled windrower, rake and large square baler is approximately 48, 39, and 21 dry tons per hour, respectively (M. Herron, 2012. Throughput of harvest equipment. AGCO. Personal communication). The windrower operator adjusts speed of equipment to achieve the working throughput capacity under different yield conditions. The operator decreases the speed of equipment if the yield of switchgrass is high and vice versa. The speed adjustment was made by using Eq. (35) (Sokhansanj et al., 2008). If the adjusted speed of the windrower was outside the windrowers typical speed range provided by ASABE EP497.5 standards (ASABE, 2006), then the upper limit of the speed range was considered for the calculations.

$$S = S_b\left(\frac{Y_b}{Y}\right) \tag{35}$$

where, S = Adjusted speed (mph), S_b = Optimum speed for the optimum yield (mph), Y_b = Optimum yield (tons/acre), Y = Yield (tons/acre).

A 13 ft. rake powered by a 75 hp tractor was considered for the present study. Under low yield conditions varying between one to two dry tons per acre, the rake gathers switchgrass from two separate windrows into one windrow. The biomass was assumed to be packaged into 3ft. × 4ft. × 8ft. large square bales which allow better fit into the semi-trailer truck and maximize load per trip.

Kemmerer and Liu (2012) found that the harvest system efficiency can be increased by balancing the field capacities of all equipment. The baler had the lowest material capacity in comparison to other operations such as raking, accumulating the bales in the field, loading the truck and stacking the bales in storage. The harvest unit was assumed to be integrated set of equipment consisting of a self-propelled windrower, a rake with a tractor and a large square baler with a tractor. The equipment in the harvest unit was matched to provide an Effective Field Capacity (EFC) of the large square baler. A harvest unit with an EFC of 25, 21, and 12 acres per hours at the yield of one, two, and three dry tons per acre, respectively was considered (Table 3).

2.3.2. In-field transportation and road transportation units

The bale stacker collects, transports, and stacks bales at the side of the field. The Stinger Stacker 6500 handles 12 bales (3 ft. × 4 ft. or 3 ft. × 3 ft.) per load. The bale handler is used to load and unload bales onto semi-trailer trucks. The EFC of bale stacker and bale handler was assumed to be 34 and 32 tons per hour, respectively. It was assumed that a 52 ft. semi-truck trailer (21 tons of biomass per load) would be used for transportation of the biomass to the biorefinery.

2.4. Economics

The cost of machinery was broken down into two categories, the fixed cost and the variable cost. The proposed model considers procuring, harvesting, transportation, and storage costs. The harvesting and transportation costs included the cost of harvest units, in-field transportation units, and road transportation units. The fixed cost of equipment was calculated using capital recovery method which included depreciation and considers wear, obsolesces, and age of machine. The variable cost was dependent on the use of machinery and comprised of repairs and maintenance (R&M), fuel and lubrication, and labor cost.

2.5. Available harvesting work hours

Switchgrass can be harvested for eight months starting in July until February of next year (Mapemba, 2005). The weather conditions determine days available for agricultural operations such as planting, cultivation, harvesting, and baling. Weather not only affects the time available for the field operation, but also the efficiency with which the operation is performed (Khanchi et al., 2013). Estimation of work-hours is crucial for making decisions for machinery management and farm planning (Rounsevell and Jones, 1993). The methodology used for estimating harvest work-hours considered weather parameters such as rainfall, snow, temperature, and wind speed. The Oklahoma Mesonet daily weather data for Steven County, KS and the adjacent counties (Morton

Table 3
Effective field capacity of equipment in a harvest unit.

Equipment	Working width (ft.)	Speed (mph)	Efficiency (%)	EFC (acres/hour)	Number of equipment in a harvest unit
Yield: 1.00 dry tons/acre					
Self-propelled windrower	16	8.0	80	12.4	2
Rake	13	8.0	80	10.1	2
Large square baler*	32	8.0	80	24.8	1
Yield: 2.00 dry tons/acre					
Self-propelled windrower	16	8.0	80	12.4	2
Rake	13	8.0	80	10.1	2
Large square baler*	32	6.8	80	21.0	1
Yield: 3.00 dry tons/acre					
Self-propelled windrower	16	8.0	80	12.4	1
Rake	13	8.0	80	10.1	1
Large square baler	16	4.5	80	7.0	2

[*] At low yield of switchgrass such as 1.00 and 2.00 dry tons per acre, baler working width is 32 ft. At low yields, two windrows will be brought together to get enough material for baler pick-up.

County, KS; Grant County, KS; Stanton County, KS; Seward County, KS, and Texas County, Oklahoma (OK) was used for analysis. The Oklahoma Mesonet provided Fractional water Index (FWI) values which correspond to the soil moisture content. FWI is a unitless value, ranges from zero (very dry soil) to one (very wet soil). The criterion used by researchers to determine the number of workdays is based on comparing soil moisture content to a percentage of field capacity depending on the type of soil (generally varies from 90–99.5%). In the present study, the criterion used for determining a non-workday was based on FWI values greater than 0.8. The rainfall criterion used for estimating the number of workdays lost was: 0, 1, 2, 3, and 4 workdays lost for rainfall range of 0.00–0.05, 0.06–0.19, 0.20–0.49, 0.05–0.99 and > 1.00 inches, respectively (Enz et al., 1995). The work hours available per day were calculated using Daylight Hours Explorer software (DaylightHoursExplorer008. 2010). The available harvest hours were assumed to be on 80 percent of the daylight hours. Twenty percent of the harvest work hours were assumed to be lost due to the machinery breakdown, unavailability of labor, and unforeseen events.

3. Results and discussion

The scenario optimization model was developed to minimize cost of the biomass supply to the biorefinery. The model determines the system cost, material flow, and number of machinery units purchased or rented. The optimization model was solved using Xpress-IVE version 1.22.04 (Fair Isaac Corporation ®2001–2012). The model was first analyzed for the base scenario (using parameters values described in Section 2.2–2.4) and later sensitivity analysis was done on yield, storage dry matter loss, and land rent.

3.1. Harvest work hours

The weather patterns during each weather scenario determined the number of suitable work hours for harvesting switchgrass in a certain time period. The actual weather conditions cannot be predicted in advance; therefore, the decisions about the purchase of the machinery were made based on the past weather data. This might result in excess machinery capacity during some years and insufficient machinery capacity during other years. In the present study, twelve years of weather data was considered beginning from 1997 to 2010 with each year considered as different weather scenario. Fig. 2 represents the work hours available for harvesting switchgrass in each weather scenario and time period. The average monthly harvest work hours available in each weather scenario were found to be statistically different ($P = 0.0004$). It was observed that the average work hours available for harvesting switchgrass for all harvest time periods varied from a minimum of 185 h to the maximum of 237 h in the 2009-2010 and1999-2000 weather scenario, respectively. The harvesting units were purchased/rented and deployed to the switchgrass source sites by the biorefinery. Therefore, it was assumed that the harvesting operation will be done on a rigid schedule utilizing maximum harvest hours available to minimize the cost of the biomass supply to the biorefinery.

3.2. Base scenario model results

As estimated by the model, for the base scenario the number of harvest, transportation, in-field transportation and storage stack units required were 6, 23, 7 and 3149, respectively with total cost of biomass supply system as $240,141, 00. It was estimated that the investment to the biorefinery was highest (50%) for the storage stack units. The storage stack unit is defined as a stack consisting of 180 bales. In the present model, it was assumed that a safety stock of a one-year switchgrass supply was stored at the inventory sites with bales covered with tarp and placed on gravel. The safety stock of switchgrass maintained at the inventory sites added a significant cost to the overall cost of biomass supply system. The factors considered for making decisions on purchasing equipment are harvest work hours, yield of biomass, and cost of purchasing and renting machinery. Twenty-three road transportation and five harvest units units account for 28% and 17%, respectively of the total cost of investment in purchased units by the biorefinery. In the base scenario, the yield of switchgrass was assumed to be two dry tons per acre. At low yields of biomass, rake operation is required throughout the harvesting season to gather enough switchgrass into a windrow for baler pick-up. Therefore, in the base scenario it was assumed that the harvest unit before-frost is equivalent to the harvest unit after-frost. The in-field transportation units cost was found to be relatively low compared to the cost of other units.

3.2.1. Acres leased and harvested for switchgrass production

From the model output, it was observed that permanent pasture and expired/not re-enrolled CRP land acres were selected to be leased for switchgrass production in the biomass source sites. As yield of switchgrass was assumed to be two dry tons per acre for all land categories, the decision for land category acres contracted for switchgrass production was based on rental rate of land and the weather scenario pattern. The land rental values considered were $60, $40 and $55 per acre for non-irrigated cropland, permanent pastureland, and expired/not re-enrolled CRP land, respectively. Primarily, permanent pastureland was contracted for switchgrass production. In Seward, Stanton, Haskell, and Texas County, the permanent pasture land contracted for switchgrass production was 89%, 34%, 75% and 2%, respectively. Approximately, 5% of the total expired/not re-enrolled CRP land acres were contracted in Stevens

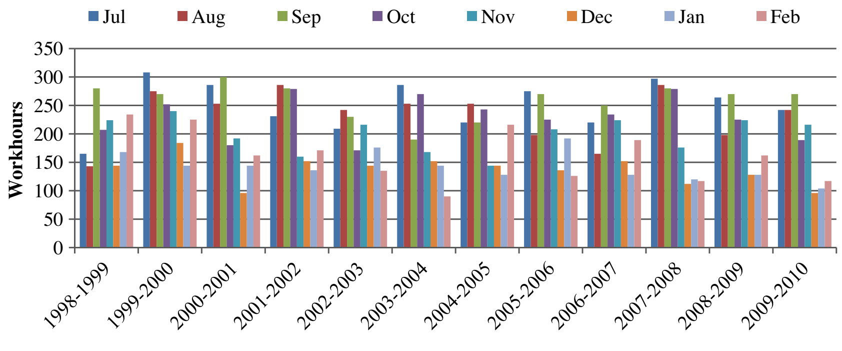

Fig. 2. Work hours available for harvesting switchgrass in each weather scenario and time period.

County by the biorefinery. The model assumes that demand of switchgrass by the biorefinery will always be satisfied. Therefore, the acres leased are sufficient to provide a regular and continuous supply of switchgrass based on yield, rental rate for land category, harvest, transportation and storage cost, and the weather scenario. All the contracted/leased acres were harvested in each weather scenario. The acres harvested in each time period of a weather scenario were dependent on harvest work hours available in the time period. The quantity of switchgrass available in each time period and weather scenario was consistent with the acres of switchgrass harvested.

3.2.2. Allocation of total harvest units to switchgrass source counties

The model allocates the harvest and in-field transportation units to the source sites depending on the quantity of biomass to be harvested at those source sites. Table 4 gives an example of the model output for a year 2009-2010, which shows allocation of harvest units during the harvest season to the switchgrass source counties. The model takes these decisions based on the work hours and the acres available for harvest from each site. Six harvest units were purchased by the biorefinery and additional capacity, if required for harvesting was achieved by renting the harvest units. It was observed that the weather scenario with least work hours rented the maximum harvest units. The 2009-2010 weather scenario had a total of 1476 work hours (minimum work hours among all weather scenarios) and therefore, rented five additional harvest units to meet the capacity. A similar trend was observed for the allocation of in-field transportation units to the switchgrass source sites.

Table 4
Allocation of total harvest units to switchgrass source counties in 2009-2010 weather scenario.

	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
Texas Co. (OK)	0	0	1	0	1	0	0	0
Morton Co. (KS)	2	1	0	2	3	0	0	0
Stanton Co. (KS)	0	0	0	0	1	0	0	2
Stevens Co. (KS)	1	4	4	1	0	0	0	0
Grant Co. (KS)	0	0	0	1	0	7	5	0
Haskell Co. (KS)	0	0	0	0	0	0	0	1
Seward Co. (KS)	3	1	1	3	1	1	1	5

3.2.3. Transportation of switchgrass

The model makes the decision for transportation of switchgrass based on two options: the feedstock can go to an inventory site before going to the biorefinery or it can directly go to the biorefinery. Depending on the demand of switchgrass, the quantity can be removed from the inventory sites in any of the time increments. For the time period with less harvest work hours lower quantities of biomass were transported to the biorefinery site. The demand for these time periods was satisfied by removing switchgrass from inventory sites. Switchgrass was stored at inventory sites to meet the demand of 120 days of non-harvesting period from March to June of a weather scenario. It was observed that switchgrass was transported to inventory sites starting from the first time period to build the inventory for non-harvesting season. In some time periods, lower quantities or no switchgrass was transported to the inventory sites. This can be attributed to lower number of harvest work hours in a time period. In case the quantity of switchgrass transported to inventory sites was not enough to meet the demand of non-harvesting time periods/months, switchgrass was purchased from outside source at a higher price. It was observed that in each time period and weather scenario, the total quantity of switchgrass harvested at source sites was equal to the sum of the quantity of switchgrass transported to the biorefinery site and inventory sites indicating no discrepancies in the model.

3.2.4. Storage of switchgrass

Switchgrass was stored and accumulated at the inventory sites to meet the demand of the biorefinery for non-harvest time periods and maintain safety stock of switchgrass at inventory sites. A safety stock for one year supply of switchgrass (280,000 dry tons) was maintained at inventory sites for beginning (July) and ending (February) time periods of a weather scenario. Stored switchgrass was also used to meet the demand of the biorefinery for time period with less harvest work hours, and also account for switchgrass losses during storage. In all weather scenarios, switchgrass was transported and accumulated at inventory sites from July-February. From March -June time period, switchgrass was removed from inventory sites to meet the demand of the biorefinery for non-harvesting periods. The ending inventory in the June time period was maintained at 280,000 dry tons. In weather scenario 2000-2001, switchgrass was removed from inventory sites in the December time period because less harvest work hours were available in the December and enough switchgrass was not harvested to meet the demand of biorefinery. The storage method selected was the uncovered bales placed on the ground. The model makes decisions on storage methods selected for storing biomass at the inventory sites based on dry matter loss and cost of the storage method. As mentioned earlier, the dry matter loss was same for both the storage alternatives and cost of storing bales unprotected on the ground was less compared to storing bales with tarp placed on gravel pad, therefore uncovered method of storage was selected.

3.3. Sensitivity analysis

3.3.1. Yield of switchgrass

The profit for the biorefinery is influenced by several factors such as feedstock type, yield, harvest work hours, biorefinery size, biorefinery location, storage losses, and transportation cost. Yield is one of the most crucial factors considered for the selection of biomass for bioethanol production and substantially changes land usage, cost, and machinery requirement to meet demands of the biorefinery. For investigating the influence of yield on model results, the scenarios of one, two, and three dry tons per acre were used as input to the model. It was observed that at the low yield of one dry tons per acre, all the switchgrass required by the biorefinery was purchased from outside source. In a real world situation, even at low yield of biomass, the biorefinery will harvest the acres contracted for the biomass production. The present model is developed for a one year planning horizon. Therefore, under a low yield of biomass, the least cost option was to procure switchgrass from outside sources. Among the three yield scenarios, the cost of the switchgrass supply to the biorefinery was least for the three dry tons per acre yield scenario. The difference in cost of switchgrass supply for two and three dry ton per acre yield scenarios was $1,249,500. At three dry tons per acre yield, the harvest unit comprised of one self-propelled windrower, two large square bale, one rake and two tractors with the Effective Field Capacity (EFC) of 12 acres per hour. When the yield was two dry tons per acre, the harvest unit comprised of two self-propelled windrower, one large square bale, two rake and two tractors with the EFC of 20 acres per hour (Table 3). The difference in cost of harvest units at two and three dry tons per acre yield was $6,035. The reason for less variation in biomass supply cost of two and three dry tons per acre yield scenario could be attributed to large difference in effective field capacity and low difference in cost of harvest units for the yield scenarios. Fewer acres were contracted at the yield of three dry tons per acre, as the demand was met due to higher yield of switchgrass.

3.3.2. Land rent and dry matter storage loss

Land rent is a crucial factor in determining the willingness of farmers to allocate their land to biomass production. As land rent increases the farmers will be more willing to grow dedicated bioenergy crops. In the present study, the effect of increase in land rental values by 15% was evaluated. Two scenarios were considered. Scenario-1 (base scenario) with the land rental values for non-irrigated cropland: $60 per acre, permanent pasture: $40 per acre, and expired- CRP: $55 per acre. Scenario-2 with the land rental values for non-irrigated cropland: $69 per acre, permanent pasture: $46 per acre, and expired- CRP: $63 per acre. It was observed that land rental rate had a significant impact on decisions for leasing acres for switchgrass production. It was observed that only permanent pasture land was contracted in scenario-2. In scenario-1 permanent pasture land and expired/not re-enrolled CRP land acres were contracted by the biorefinery. The other variables did not vary significantly.

In the base scenario, the dry matter loss was the same for both storage alternatives and the cost of storing bales uncovered was low. Therefore, the model selected the uncovered storage method as the best alternative for storing switchgrass. Sensitivity analysis was also performed to evaluate the effect of dry matter loss on allocation of the method selected for switchgrass storage. For the present study, the base scenario (scenario-1) was compared to scenario-2 with dry matter loss for unprotected (bales uncovered and placed on the ground) and protected (bales covered with tarp and placed on gravel) storage methods as three (0.66%) and four (1.33%) times higher than the value considered in the base scenario, respectively. The results indicate that as dry matter loss increases, the acres contracted to meet the demand of biorefinery also increases. One extra harvest unit was also purchased for harvesting extra acres in the case of high dry matter loss scenario.

4. Conclusion

A scenario optimization model considering weather uncertainty was developed. Harvest work hours influenced major cost-related decisions in the BSC. The method of biomass storage was dependent on the cost and dry matter loss during storage. Yield of biomass was found to be a crucial factor in determining the feasibility of BSC system. The model captures weather uncertainty and its influence on purchasing and deployment of assets. The direction for future research will be to consider different types of biomass feedstocks, conversion processes, and environmental impact of biofuel production into the model.

References

Akgul, O., Zamboni, A., Bezzo, F., Shah, N., Papageorgiou, L.G., 2010. Optimization-based approaches for bioethanol supply chains. Ind. Eng. Chem. Res. 50 (9), 4927–4938.

An, H., Wilhelm, W.E., Searcy, S.W., 2011. A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. Bioresour. Technol. 102 (17), 7860–7870.

ASABE. 2006. EP496.3. Agricultural machinery management. ASABE Standards, American Society of Agricultural Engineers. St. Joseph, Michigan, USA.

Bevill, K. 2011. Abengoa offers details on biomass supply agreement. In: Ethanol producer Magazine, April. http://ethanolproducer.com/articles/7703/abengoa-offers-details-on-biomass-supply-agreement. Accessed: December 10, 2011.

BP. 2013. BP outlook 2030. Why biofuels. http://www.bp.com/sectionarticle.so?categoryId=9030039&contentId=7055156. Accessed: January 5, 2013.

Chen, C.W., Fan, Y., 2012. Bioethanol supply chain system planning under supply and demand uncertainties. Transp. Res. E. Log. 48 (1), 150–164.

Christensen, C.A., Koppenjan, G., 2010. Planting and managing switchgrass as a dedicated energy crops. Blade Energy Crops. http://www.bladeenergy.com/Bladepdf/Blade-Switchgrass-Mgmt_2ed.pdf. Accessed: August 10, 2011.

Cundiff, J.S., Dias, N., Sherali, H.D., 1997. A linear programming approach for designing a herbaceous biomass delivery system. Bioresour. Technol. 59 (1), 47–55.

Dal-Mas, M., Giarola, S., Zamboni, A., Bezzo, F., 2011. Strategic design and investment capacity planning of the ethanol supply chain under price uncertainty. Biomass Bioenergy 35 (5), 2059–2071.

DOE/EIS. 2010. Final environmental impact statement for the proposed Abengoa Biorefinery Project near Hugoton, Stevens County, Kansas. Office of Energy Efficiency and Renewable Energy. http://www.doe.gov/nepa/downloads/eis-0407-final-environmental-impact-statement.

Dunnett, A., Adjiman, C., Shah, N., 2007. Biomass to heat supply chains applications of process optimization. Process Saf. Environ. 85 (5), 419–429.

Eksioglu, S.D., Acharya, A., Leightley, L.E., Arora, S., 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. Comput. Ind. Eng. 57 (4), 1342–1352.

Enz, J.W., Helm, J.L., Brenk, P.C. 1995. Potential field work days during planting and harvesting. http://www.ag.ndsu.edu/pubs/plantsci/crops/a1008w.htm. Accessed: September 24, 2011.

Epplin, F.M., Clark, C.D., Roberts, R.K., Hwang, S., 2007. Challenges to the development of a dedicated energy crop. Am. J. Agr. Econ. 89 (5), 1296–1302.

Giarola, S., Shah, N., Bezzo, F., 2012. A comprehensive approach to the design of ethanol supply chains including carbon trading effects. Bioresour. Technol. 107, 175–185.

Gunnarsson, H., Rönnqvist, M., Lundgren, J.T., 2004. Supply chain modelling of forest fuel. Eur. J. Oper. Res. 158 (1), 103–123.

Huang, H.J., Lin, W., Ramaswamy, S., Tschirner, U., 2009. Process modeling of comprehensive integrated forest biorefinery-an integrated approach. Appl. Biochem. Biotechnol. 154 (1), 26–37.

Huang, Y., Chen, C.W., Fan, Y., 2010. Multistage optimization of the supply chains of biofuels. Transp. Res. E. Log. 46 (6), 820–830.

ICC (International Code Council), 2003. International Fire Code. International Code Council, Inc.

Kemmerer, B., Liu, J., 2012. Large square baling and bale handling efficiency-a case study. Agr. Sci. 3 (2), 178–183.

Khanchi, A., Jones, C.L., Sharma, B., Huhnke, R.L., Weckler, P., Maness, N.O. 2013. An empirical model to predict infield thin layer drying rate of cut switchgrass. Biomass Bioenergy, in press.

Khanna, M., Chen, X., Huang, H., Onal, H., 2011. Supply of cellulosic biofuel feedstocks and regional production patterns. Am. J. Agr. Econ. 93 (2), 473–480.

Koss, W.J., Owenby, J.R., Steurer, P.M., Ezell, D.S., 1998. Freeze and frost data. Supplement No. 1. National Oceanic and Atmospheric Administration, U.S. Department of Commerce. http://www.ncdc.noaa.gov/.

Mapemba, L.D. 2005. Cost to deliver lignocellulosic biomass to a biorefinery. Ph.D. Dissertation. Oklahoma State University, Stillwater, Oklahoma, USA, pp. 1-275.

Mesonet., 2012. Past data and files. Oklahoma. http://www.mesonet.org/index.php/weather/category/past_data_files. Accessed: November 10, 2012.

Perlack, R.D., Stokes, B.J. 2011. U.S. Billion-ton update: Biomass supply for a bioenergy and bioproducts industry. Oak Ridge National Laboratory and U.S. Department of Energy ORNL/TM-2011/224. Oak Ridge, Tennessee, USA.

Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. DOE/GO-102005-2135 and ORNL/TM-2005/66. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Rounsevell, M.D.A., Jones, R.J.A., 1993. A soil and agroclimatic model for estimating machinery work-days: the basic model and climatic sensitivity. Soil Till. Res. 26 (3), 179–191.

Sharma, B., Jones, C.L., Khanchi, A., 2011. Tensile strength and shear strength of switchgrass before and after frost. Bio. Eng. 4 (1), 43–54.

Sharma, B., Ingalls, R.G., Jones, C.L., Khanchi, A., 2013. Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. Renewable Sustainable Energy Rev. 24, 608–627.

Sokhansanj, S., Turhollow, A., Wilkerson, E. 2008 Development of the integrated biomass supply analysis and logistics model (IBSAL) Oak Ridge National Laboratory and U.S. Department of Energy ORNL/TM-2006/57. Oak Ridge, Tennessee, USA.

Svanberg, M., Olofsson, I., Flodén, J., Nordin, A., 2013. Analysing biomass torrefaction supply chain costs. Bioresour. Technol. 142, 287–296.

Tembo, G., Epplin, F.M., Huhnke, R.L., 2003. Integrative investment appraisal of a lignocellulosic biomass-to-ethanol industry. J. Agr. Resour. Econ. 28 (3), 611–633.

You, F., Wang, B., 2011. Life cycle optimization of biomass-to-liquids supply chains with distributed-centralized processing networks. Ind. Eng. Chem. Res. 50 (17), 10102–10127.

You, F., Tao, L., Graziano, D.J., Snyder, S.W., 2011. Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis. J. Am. Chem. Soc. 58 (4), 1157–1180.

Zamboni, A., Shah, N., Bezzo, F., 2009. Spatially explicit static model for the strategic design of future bioethanol production systems. 1. Cost minimization.. Energy Fuels 23 (10), 5121–5133.